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VARIABLE-CYCLE ENGINES FOR SUPERSONIC CRUISE AIRCRAFT

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SUMMARY

Since 1973, the NASA Lewis Research Center has been conducting studies of advanced civil supersonic engines, including Variable Cycle Engines or VCE's, as one part of the Supersonic Cruise Aircraft Research (SCAR) program. This paper reviews the progress and current status of the engine study work to date.

VCE rationale is first reviewed. It is pointed out that the VCE is a possible means of reconciling the necessary but sometimes contradictory performance, economic and environmental requirements that apply to modern supersonic-cruise aircraft. Early experiences showed, however, that VCE's may be excessively complex, heavy and expensive unless significant technology advances are accomplished. The SCAR engine studies were, therefore, designed to identify the most promising VCE concepts, simplify their designs to a more practical state, and define their advanced technology requirements.

The studies were conducted primarily via contracts, supplemented by a lesser amount of NASA in-house work. Initial efforts involved analyzing, optimistically but in little depth, a large variety of VCE concepts. In subsequent phases, a progressively-greater depth of analysis was applied to a decreasing number of surviving candidates. The line of development leading from initial to final concepts is reviewed with emphasis on the dual impact of technology advancements and design simplification. The presently-favored VCE's (two P&W concepts derived from a duct-burning turbofan and two GE engines based on a mixed-flow turbofan) are then reviewed. It is shown that all have benefitted significantly from recent SCAR technology advances, such as the "co-annular noise benefit" effect. The impact of each technology area is discussed. It is also shown that these simplified VCE cycles and technology advances, taken together, offer major performance, economic and environmental improvements relative to the 1970 U.S. SST predictions.

It is concluded that final choices among the current VCE candidates will depend on application and installation factors as well as further engine study/design and technology efforts. NASA's tentative plans in these latter respects are reviewed in the final section of the paper.

INTRODUCTION

Since early 1973, the NASA and its Contractors have been conducting studies of advanced supersonic Variable Cycle Engines (VCE's) as part of the Supersonic Cruise Aircraft Research (SCAR) program. This paper surveys the progress and current status of recent, unclassified engine study work.

Technical, economic and environmental problems were sources of major concern which eventually led to the cancellation of the U.S. SST program in 1970. Major environmental concerns were primarily focussed upon the engine's noise and exhaust emissions, as illustrated in Fig. 1. Other technical and economic problems were attributable partly to the propulsion system and partly to the airplane. These resulted in excessive weight and cost of the airplane, together with high fuel consumption and inadequate range. Consequently, this airplane would have been unable to serve many of the economically desirable city pair combinations. These factors would have caused the airplane to be costly to operate and to offer a relatively poor return on its investment. Inflation together with recent increases in the price of fuel would have made the situation even worse today.

The one unmistakable lesson to be learned from this experience is that any future U.S. civil supersonic airplane must be environmentally acceptable and economically viable. The sometimes-conflicting requirements of economic viability and environmental acceptability create major problems for the propulsion system. Their practical engineering solutions entail essentially contradictory design trends, e.g., high bypass vs. low bypass. Unfortunately we cannot turn to contemporaty engines for relief. The U.S. J58 and J93, although capable of cruising at Mach 3 or above, are relatively old designs and are not suitable for an advanced supersonic transport. Modern U.S. military engines such as the F100, J101, and F101 were essentially designed for sustained subsonic cruise efficiency with only a high Mach number dash capability. Their performance and service life characteristics for sustained supersonic cruise would be unacceptable for the applications envisioned now.

There are many ways to build a VCE and, as a matter of historical interest, some of the early ideas are described in refs. 1 & 2. For this discussion, however, a VCE is best defined by what it does rather than how it is built. Functionally, it is an engine which accommodates at least two distinct modes of operation: (1) a high airflow, low jet-velocity mode for low noise takeoff and/or efficient subsonic cruise; and (2) a turbojet-like, higher jet velocity, lower airflow mode for good supersonic cruise.

In more technical terms, the motivation for this "turbofan-convertible- to-turbojet" definition may be understood by reference to Fig. 2. There, weight and cruise-SFC trends for conventional supersonic engines are presented in terms of bypass ratio. Clearly, both weight and subsonic fuel economy favor a fairly high bypass ratio, about 1.5 (turbofan mode). Supersonic cruise on the other hand calls for a low bypass engine, 0.3 or below when fuel economy is considered, but this is tempered somewhat by the adverse weight trend. With a conventional engine, a compromise bypass ratio (usually in the 0.5 to 1.5 range, depending on the subsonic/supersonic mission mix) must be chosen, which is not really optimum for either requirement. The rationale for a VCE, then, is its potential ability to give use a better compromise. For this reason, the SCAR propulsion program was oriented to include VCE concepts and related technologies in addition to advanced conventional engines. It consists of studies and related technology subprograms which, collectively, were designed to identify, develop, and integrate together the technologies needed for a successful VCE. The study phase of the program is of primary concern in this paper.

The SCAR Propulsion studies were conducted primarily via contracts to GE and P&W, with a major subcontract to Boeing. Early phases of the studies involved analyzing, optimistically but in little depth, a large variety of VCE concepts. The results showed that VCE's may be prohibitively complex, heavy and expensive unless significant design and technology advances are accomplished. The final phases were, therefore, intended to identify, refine and compare the most promising VCE concepts, simplify their designs toward practicality and define their advanced technology requirements. The presently-favored and runner-up engines (a P&W advanced duct-burning turbofan, a P&W valved derivative of the duct-burner and two GE engines based on a mixed-flow turbofan) are first reviewed. Their performance in typical advanced supersonic transport airframes is then compared to that provided by first-generation SST engines. The impact of each major technology area is discussed and the technology needs of the preferred engines are reviewed.

The final fate of the VCE idea will depend on application and installation factors, further engine design and technology efforts, and the possible emergence of even more attractive VCE cycles from continuing studies. Future issues, options, and potential program plans in these areas are briefly reviewed in the final section of the paper.

THE SUPERSONIC CRUISE AIRCRAFT RESEARCH PROGRAM

The NASA Supersonic Cruise Aircraft Research (SCAR) program was instituted in early 1973 and is expected to continue into the 1980's. In contrast to the earlier SST project, the SCAR work is not aimed toward a production airplane, but rather, it is intended to establish a data base of advanced technology to be available for the design of future supersonic cruise aircraft if and when the U.S. determines it is desirable to build them. The various elements of the program are relevent in varying degrees to both potential civil and military applications. Elements of the program apply both to the airplane structure and aerodynamics and to the propulsion system; however, only the propulsion related aspects will be discussed here. As shown on Fig. 3, the SCAR propulsion program consists of two major, interrelated elements; namely, engine studies and technology sub-programs. These are so structured that one supports the other. The engine studies define the objectives and directions of research for the technology sub-programs. The results from the technology sub-programs in turn feed back into the engine studies and regenerate them. As indicated above, the engine studies have been conducted primarily by means of a continuing series of contracts to the Pratt & Whitney Co. (refs. 3 and 4) and the General Electric Co. (refs. 5 and 6), with a major sub-contract between P&W and The Boeing Co. (described in refs. 4, 7-9). Technology sub-programs involving these contractors as well as others have been launched in the areas of noise abatement (refs. 10-13), pollution reduction (refs. 14-16), inlet stability (ref. 17), and supporting component and material programs (e.g., ref. 18). References 19 and 20 survey the SCAR propulsion and airplane technology programs sponsored by the NASA Lewis and Langley Research Centers.

Before elaborating on these programs, we would like to illustrate the type of advancements are are considered possible now, based on results to date from the SCAR program. In Fig. 4, we have plotted airplane relative gross weight vs. relative noise footprint area (a typical measure of noise annoyance) for representative supersonic transport airplanes with different kinds of engines. These are approximate results taken from ref. 21 but are illustrative of the major trends. For reference, we have indicated on the horizontal axis the noise annoyance factors typical of the 1970 U.S. SST (at the right hand part of the scale) and also of a representative wide body subsonic transport. The performance of the 1970 technology turbojet powered airplane is illustrated by the right hand band on the figure. As mentioned previously, this was a heavy airplane and would have created a severe noise impact. Although the noise impact could be decreased by scaling the engine up in size and throttling it back for takeoff, this entails a substantial weight penalty as indicated. This in turn makes an already dubious economic payoff entirely unacceptable. But by taking advantage of the technology breakthrough termed the "co-annular noise reduction benefit" identified during the SCAR propulsion program, combined with variable cycle engine concepts to be discussed later, it now appears that the noise annoyance due to this type of an airplane can be reduced by a large factor compared to the 1970 U.S. SST. A less dramatic but still significant improvement in gross weight and airplane economics is also indicated and is due to a combination of many technology advances, in both the propulsion and airframe areas, that are considered possible.

Because of these promising developments we now feel, for the first time, that the noise objections that were leveled against the 1970 SST program can be met without incurring prohibitive economic penalties. An equivalent statement cannot yet be made in the exhaust emissions area, despite the achievement of significant improvements, because realistic standards applicable to an SST do not exist at present.

Engine Studies

Let us now turn to the SCAR engine studies themselves. Beginning in 1973, the studies have been divided into 4 distinct phases as indicated in Fig. 5. Phase 1 was organized in such a way as to exclude no reasonable candidate engine from consideration. Many engines were studied optimistically but in very little depth, see refs. 3 and 5. Only those engines which were obviously unacceptable under this optimistic approach were excluded from further consideration. Our deliberate intent was to give the Variable Cycle Engine its day in court. After the unpromising concepts had been screened out, a smaller number of survivors received a more refined analysis in Phase 2 (refs. 4 and 6). Four finalists survived into Phase 3 which has just recently been completed and is as-yet unpublished. In this phase a greater depth of analysis was accomplished and we initiated preliminary design activities. Based on the results, we have now tentatively identified two engines which appear to be most promising. (Their margins of superiority, however, are not overwhelmingly large; the runners-up are being retained as backups and will also be described.) In Phase 4 we are initiating airframe integration activities, continuing with preliminary design and developing a series of technology recommendations relative to the favored engines. These provide the engine manufacturers with an opportunity to define, for NASA's consideration, what is needed in terms of future technology programs in order to bring these paper engines into being. As illustrated by the arrow in the upper right we expect that these activities will eventually result in demonstrator engines which will prove the concepts that are being contemplated.

Before proceeding to a discussion of the currently-favored engines, it seems appropriate to briefly review the evolution of the VCE idea and describe how it may be impacted by two major technology area.

Early VCE Concepts

According to our previous definition, a VCE is an engine that <u>does</u> the right things. The many attempts that have been made to actually design one may be broadly classified into two generic approaches. One would rely upon valves or equivalent means to create two or more discrete flowpaths upon demand within the same engine structure - each flow path presumably being tailored to the flight condition at hand. The alternative approach would rely primarily upon component variability and spool speed variations to achieve equivalent results.

A typical early example (Pratt & Whitney, ref. 3) of the changing-flowpath approach is shown in Fig. 6. Here a valve is inserted between the fan and compressor of an otherwise-conventional 2-shaft machine. In the "turbojet" mode, the valve is set in its straight-through position. The fan and compressor flow in series, and we have in effect a two-spool, high overall-pressure-ratio (OPR) turbojet. As such, it can provide very good supersonic performance. In the "turbofan" mode, the valve mechanism is moved to the "crossover" position suggested by the lower sketch. Fan air supplied by the normal inlet is bypassed around the compressor and into an auxiliary bypass duct. Meanwhile, additional air from an auxiliary inlet is drawn through a second set of channels in the valve, into the compressor, and hence, through the combustor and turbines. Thus, the engine is now operating at a much higher (up to 2X) airflow than before and without augmentation its jet velocity is significantly decreased. In this mode, the engine provides a low-noise takeoff mode and potentially good subsonic SFC.

By the standards of our functional definition, this engine does the right things. Numerous objections, however, were found upon closer examination. From an engine manufacturer's viewpoint, it developed that the weight and pressure-loss penalties associated with the valve were significantly larger than had been expected. Since the core is desupercharged in the turbofan (parallel) mode, the OPR is considerably below the optimum value for subsonic cruise. For the same reason a variable (and probably multi-stage) low-pressure turbine would be needed to provide high relative work extraction in the turbofan mode, and lower extraction in the turbojet mode. From the airframe point of view it was observed that the requirement for an efficient auxiliary inlet implied a major design and development task and a significant additional installed-weight penalty (above that required to enclose the engine's greater length and diameter). The closed-off bypass duct also would entail a sizable base or boattail drag penalty during supersonic cruise.

Subsequent efforts were aimed at removing or minimizing these complications. As described in ref. 4, many alternatives involving front valves, rear valves, front and rear valves, and improved valve concepts were evaluated iteratively by Pratt & Whitney and Boeing. An historical review of this process is given in ref. 22, where it is shown that the lessons learned also apply, to some degree, to more conventional engines. The rear-valved VCE to be described later herein, is the latest and apparently best example of this particular line of VCE evolution, but probably not its end-point.

The variable-component/variable speed approach is most attractively represented by the Pratt & Whitney Variable Stream Control Engine. Essentially a high-technology duct burning turbofan incorporating some of the component and control features discussed in ref. 22, it is currently the favored P&W VCE and will be more fully described later.

Another historically-significant and perhaps more spectacular example is the General-Electric 3-Spool Double Bypass or Modulating Airflow Engine (ref. 5) depicted in Fig. 7. It is a representative sample of the early variable-component approach, although there are many others. It is of particular interest here because it was not only the best VCE identified in the initial GE studies (ref. 5), but also because many of its characteristic features have survived into their currently-favored, much-simplified version of the Double Bypass VCE.

The design approach for this engine was to incorporate the maximum practicable amount of turbomachinery variability into a basic duct-burning turbofan. By utilizing differential speed control among the three rotors, variable stator geometry and properly controlling the three variable nozzle exit areas, it provides (1) a high-airflow, unaugmented mode for low-noise takeoff; (2) a constant-airflow throttling mode for efficient subsonic cruise; and (3) a relatively low-bypass augmented mode for good supersonic performance.

At takeoff, the front fan block or group of stages was high flowed by means of variable geometry, speed control (i.e. speeding-up the inner spool) and opening the outer bypass stream's exit area. The duct burner is not lit. Without using either a mechanical suppressor or the "co-annular benefit" (which was unknown at the time), the Modulating Airflow engine was capable of meeting FAR 36 when sized to be competitive with a conventional reference engine.

Subsonic cruise throttling is accomplished by running the inner rotor at essentially constant speed; the front fan block then maintains its constant nominal airflow over a wide range of conditions. The intermediate and high pressure rotor speeds are varied to modulate the thrust. The excess air provided by the front block (above the intermediate block's air-swallowing capacity) passes through the outer duct to the third nozzle exit. The duct burner is not lit. In this fashion, constant airflow could be maintained down to approximately 50% of maximum dry thrust. This provided a significant (~15%) improvement in subsonic SFC.

At supersonic cruise, the rotor speeds and variable geometry features are modulated to approach turbojet operation as closely as possible. That is, the high pressure and intermediate rotors are run at maximum speed to swallow most of the front block's airflow. The outer nozzle meanwhile is at or near the closed position to minimize the outer bypass flow. The core is run at maximum speed and is high-flowed to swallow as much as possible of the intermediate block's air. This reduces the bypass ratio of the duct-burner portion of the engine and hence the need for augmentation. When run in this manner, the engine's supersonic cruise performance was found to be within 1 or 2% of that of the reference turbojet.

Similar measures applied during the mission's climb/accel segment resulted in a consistently good match to the inlet's flow schedule and hence fuel savings via reduction of installation drags.

Thus, the 3-Rotor Double Bypass or Modulating Airflow engine also does everything required of a VCE: low noise takeoff; fuel savings subsonically and during the climb/accel phase; and competitive supersonic performance. Unfortunately, these desirable features were essentially offset by a major weight penalty (amounting to over 20,000 lbs per airplane, when installed). Depending upon the flight Mach number, the resulting airplane's performance ranged from just competitive to somewhat poorer. Because of the weight penalty together with very legitimate concerns over the engine's complexity, the 3-rotor approach was not continued pas the Phase I SCAR studies. Instead, an effort was made to incorporate its most desirable features into a lighter, less complex and more conventional 2-shaft machine. The concept was retained of dividing the fan into two distinct blocks or groups of stages, with the interblock region ventilated by an auxiliary bypass duct. As will be seen, this progress in design simplification, coupled with the technology advances discussed in the next two sections, has finally resulted in a highly attractive VCE.

The Co-annular Noise Benefit

As previously implied, the "Co-annular Noise Benefit" effect is considered to be the major "break through" in the SCAR propulsion technology program. Figure 8 illustrates what is meant. Attention is first directed to the lower right hand corner of the figure. In brief, it has been found that: (a) if the flow streams of a two stream coaxial nozzle are so arranged that the high velocity stream is one the outside and the low velocity stream is on the inside; and (b) if in addition the outer nozzle has a high annular radius ratio; then the noise produced by this arrangement is significantly lower than would be predicted for two conventional conical nozzles which individually have the same airflows and velocities as in the two coaxial streams. This effect was first noted by Pratt & Whitney during SCAR parametric acoustic testing that commenced in 1974 (refs. 10-13) and was later confirmed by parallel independent testing at General Electric (as-yet unpublished). It is of the utmost significance for SCAR VCE concepts since these inherently involve (or can be so arranged as to provide) a coaxial, high radius ratio two stream nozzle flow configuration at takeoff.

It should be noted that both the coaxial flow configuration and the high annular radius ratio are necessary to obtain the maximum benefit. The term "co-annular" is, therefore, used as a reminder of this fact.

The rest of the chart illustrates the sideline noise produced by either conventional or co-annular nozzles as a function of the jet velocity averaged over the two streams. Two bands are shown, the upper one for conventional nozzles and the lower one for co-annular nozzles. As indicated by the vertical line, the 1970 turbojet operated at a relatively high jet velocity and created a noise signature 12 to 15 dB above the FAR 36 requirement. This could be reduced to some degree by oversizing the engine and operating it throttled back to lower jet velocities for takeoff purposes. As previously mentioned, however, this results in severe airplane weight and economic performance penalties; so severe, in fact, as to be unacceptable. When a co-annular nozzle is used, on the other hand, it is immediately seen that the noise signature is 8 to 10 dB lower than that of the conventional model. If in addition, the engine is a variable cycle engine which is capable of taking-off at reduced jet velocities without otherwise penalizing the airplane, it may be seen that a noise signature below FAR 36 can be anticipated. The combination of the two concepts, namely, the co-annular nozzle and the variable cycle engine, results in perhaps 10 - 12 dB lower noise than that of the conventional nozzle combined with the conventional turbojet engine. This, it is felt, will have a decisive impact on the environmental acceptability of any future SST.

The application of this revolutionary concept to a duct-burning turbofan engine is straightforward. The flow stream configuration is already the proper one, it is only necessary to tailor the cycle to provide the correct velocity and radius ratios. It is also adaptable to some mixed-flow engines via the use of a ventilated plug nozzle of the general type discussed in refs. 23-25. In essence, fan air or inlet ram air is ducted to the plug by some means and exhausted from an annular slot in the afterbody. The above-mentioned General Electric acoustical research program has shown that, depending on radius ratio and flow conditions, most of the benefit illustrated in Fig. 4 may be achieved by this arrangement.

Pollution - Reduction Technology

Let us now turn to the second area of environmental concern, namely, exhaust emissions. Of the various emission criteria, that of high altitude cruise NOX is of greatest concern for the supersonic transport. In Fig. 9, we illustrate the comparative performance of several combustor concepts in terms of its relative NOX emission index at supersonic cruise. As indicated by the top bar, a conventional combustor such as was used in the 1970 SST and is still used today in current airplanes, shows the highest emission level and is normalized to 1.0 on this relative scale. (The normalizing factor varies from about 20 gm/kg to 50$^+$ gm/kg depending on cycle conditions.) This may be compared to a value of 3 gm/kg (0.16 to 0.06 relative) which ref. 26 tentatively suggests may be appropriate for the avoidance of appreciable stratospheric pollution by a future SST fleet. The clean combustor concepts developed by Pratt & Whitney and General Electric under our recent SCAR Experimental Clean Combustor Program (refs. 14 & 15) show relative emission indices of approximately 0.4 to 0.5, on the same scale, in burner-rig experiments. This level of performance could be incorporated in a new engine program starting now. Further improvement is predicted for NASA's swirl can combustors and various lean combustor concepts. Probably the most hopeful concepts for the future, however, are in the area of pre-mix combustors and the catalytic combustor concept (e.g., ref. 16). NOX indices as low as 1 gm/kg (0.05 to 0.02 relative) have been demonstrated in small scale, idealized laboratory experiments. But it is clear that a large, lengthy and probably expensive program, including both fundamental research work and applied development, will be required to translate these promising concepts into reality. Assuming that the necessary programs will be forthcoming, we anticipate that relative values as low as 0.25 may eventually be attainable in practical engines. (Absolute levels of course will also depend upon the specific cycles chosen.) It should be recognized, however, that this involves our entering a new and relatively unknown area of technology, and this has yet to be done in a serious way. The above estimates are therefore uncertain, as are the projected requirements; either or both may change significantly in the future.

Although NOX emissions are most critical for an SST, it must be recognized that local (airport-area) emissions must also be environmentally acceptable. It is believed, however, that all of the advanced technology primary burner concepts would be capable of meeting the "proposed" standards for future SST's.

This is not necessarily the case for augmentors, however. The search for a locally-acceptable augmentor will again require us to enter an uncharted technology area.

CURRENT VCE's

Having reviewed early VCE concepts and two major impacting technology area, it is now appropriate to turn to the currently favored VCE's themselves. These "paper" engines are the "final product" of the SCAR engine studies. Further, more refined definitions of these engines must await the outcome of hardware oriented programs.

Pratt & Whitney Concepts

The currently-favored Pratt & Whitney VCE is illustrated in Fig. 10. This Variable Stream Control Engine (VSCE) has the flow path of a conventional duct burning turbofan. But it incorporates an unique main combustor power schedule and makes extensive use of rotor speed control and variable geometry in the fan, compressor, primary nozzle, and secondary nozzle to control its operating bypass ratio. Because of this capability, the VSCE qualifies to be termed a variable cycle engine. Yet it is of striking simplicity in comparison with the approaches illustrated previously in Figs. 6 and 7.

Under subsonic cruise conditions the duct burner is not lit. The engine then is precisely a conventional separate flow medium bypass turbofan engine (bypass $\approx$ 1.5) and it provides relatively good subsonic cruise performance.

For takeoff, acceleration and supersonic cruise, however, additional thrust is required. This is obtained by lighting the duct burner. During takeoff, the additional energy supplied by the duct burner results in higher velocity in the nozzle's outer annular stream. But the additional noise implied by this condition is offset by the co-annular noise reduction benefit that was discussed earlier. Thus, the engine, when taking off, should sound more like a conventional turbofan engine than like a high-performance supersonic engine. During supersonic cruise operation the core is speeded up by increasing the temperature in the main combustor and by manipulating variable geometry features. Thereby, the bypass ratio is decreased and the need for augmentation is decreased, resulting in specific fuel consumption approaching that of a well designed turbojet engine.

The second Pratt & Whitney VCE is depicted in Fig. 11. This Rear Valve VCE (VCE-112C) is derived from the duct burning turbofan through the addition of a mixer/crossover valve followed by an additional aft turbine stage - both located downstream of the normal LPT. The VCE-112C has two distinct operating modes depending on the valve position. For takeoff, acceleration and supersonic cruise, the valve is in the "crossover" position. I.e., core air bypasses around the aft turbine and exits through the outer annulus of the nozzle. Thus, the core cycle is that of a turbojet.

The fan air meanwhile passes through the duct burner (which is lit), and is directed by the crossover valve into the aft turbine, where a significant amount of energy is extracted to help drive the LP system. The fan air's cycle is also that of a turbojet; hence, this mode of operation is referred to as the "twin-turbojet mode." Its supersonic performance, however, is not quite as favorable as this name implies, because neither "turbojet" cycle is of the optimum pressure ratio and because of pressure losses and weight/volume penalties due to the valve and aft turbine. Its advantages are relatively low weight (due to the high "bypass" ratio of about 2.5) and an advantageously-shaped supersonic throttle curve. I.e., since the duct burner is upstream of a turbine stage, high augmentations can be accomplished for significantly less SFC penalty than in the VSCE's case. The resulting "flat" throttle curve in turn provides the airplane designer with additional flexibility in terms of engine sizing.

Subsonically, the valve is in the "mix" position and the duct burner is not lit. The combined fan and core streams pass through the aft turbine. The corrected flow is about the same as that provided by the augmented fan stream alone in the supersonic twin-turbojet mode. The aft turbine, however, extracts relatively little power. The engine thus behaves as if it were a conventional mixed flow turbofan for subsonic cruise.

A major disadvantage of the VCE-112C is that the earlier-discussed coannular noise benefit may not apply fully. That is, the nozzle's central stream at takeoff (which originated in the duct burner) is relatively large and of high velocity compared to that of the VSCE. There is hence a core jet noise "floor" which will probably limit the co-annular benefit to no more than 50% of that shown in Fig. 5.

A third Pratt & Whitney engine of interest (but not illustrated herein) is a modernized conventional mixed flow turbofan with a relatively low (0.4) bypass ratio known as LBE-430. Although lacking obvious VCE features such as valves or coaxial flow streams, it incorporates the identical general technology assumptions (materials, temperatures, component efficiencies, stresses, cooling techniques, etc.) that were built-into the Pratt & Whitney VCE's. It also utilizes rotor speed control and variable geometry features (to the extent possible) as in the VSCE-502B, to maintain a degree of control over the operating bypass ratio. As will be seen later, it provides excellent performance at low airflow sizes if noise constraints are ignored. Unfortunately, the coannular benefit does not apply to this engine in its present form. Hence, this engine, alone among those considered herein, would require either the use of a mechanical noise suppressor (with its attendant risks and penalties) or a greatly-oversized engine for throttled-back takeoff. It is a useful yardstick, however, for evaluating the merits of the coaxial-stream VCE concepts.

General Electric Concepts

The other preferred VCE concept is the General Electric Double Bypass Engine (DBE) shown in Fig. 12. Like the Pratt & Whitney engine, it is designed to take full advantage of the annular/coannular noise benefit, clean primary burners and augmentors, advanced materials and other SCAR technology developments. But where the Pratt & Whitney engine originated as a duct burning turbofan, the double bypass engine is derived from a conventional mixed flow turbofan by adding features from the 3-rotor engine previously discussed.

The low bypass mixed flow engine can provide excellent supersonic performance, but is prone to be excessively heavy when its airflow is sized for low noise takeoff. As with all conventional turbofans, it also suffers from a significant throttle dependent drag penalty at part power subsonic cruise because airflow decreases along with thrust when the engine is throttled back. To offset these penalties, the double bypass engine provides a temporary high airflow mode for low noise takeoff and the capability to throttle at constant airflow for part power subsonic cruise.

As the figure suggests, this is physically accomplished by dividing the fan into two distinct blocks or groups of stages, and providing an auxiliary duct leading from the interblock region. The resulting flow path is similar to that of the 3-rotor engine, but major progress in design simplification has been achieved - as may be inferred by comparing Fig. 12 with Fig. 7. Although not illustrated here, some of the auxiliary flow can discharge into the plug and exit from the aft surface through an annular slot. This provides the flow configuration and geometry needed to obtain the coannular noise benefit discussed earlier.

Three distinct operating modes may be recognized, depending on the fan block flow settings and whether the auxiliary duct is open or closed.

In the low noise takeoff mode, the auxiliary duct is open, the front fan block is in its high flow setting, the core is operated at maximum takeoff power, and maximum energy is extracted by the low pressure turbine. The tailpipe heater is not lit. In this mode, the double bypass engine provides thrust, airflow and jet velocity characteristics that would be typical of a larger but throttled back conventional engine, or a higher bypass engine. Note, however, that only the front block is high flowed. Hence, there is significant weight savings compared to an equal noise conventional engine. The combination of lower mean jet velocity with the coannular noise benefit results in an engine that is remarkably quiet for its power.

For part power subsonic cruise, the auxiliary duct is again open, and passes the excess airflow provided by the front block. In this fashion, a wide range of throttling may be accomplished at constant airflow, thereby eliminating or minimizing spillage, boattail, and other throttle dependent drags.

In the high power mode for climb, acceleration and supersonic cruise, the auxiliary duct is closed, the core is at or near maximum continuous power, and the tailpipe heater is used as needed. In this mode, the double bypass cycle is identical to that of the conventional low bypass engine, and offers essentially the same performance.

A second General Electric VCE of potential interest is the Dual Cycle Engine or DCE (not illustrated herein). It is also a derivative of the low-bypass mixed flow turbofan, but in this case a relatively simple one. As its name implies it has two modes of operation - mixed flow and separate flow. The conventional mixed flow mode is used for climb, acceleration and supersonic cruise. For takeoff or subsonic cruise, the bypass stream is diverted from the normal mixer and instead exits through a separate nozzle opening. This allows the engine to throttle at constant airflow over a range about midway between the conventional turbofan and the DBE. Since the separated bypass flow could also be led to the plug as in the DBE, the coannular benefit is believed to be applicable. As will be seen, this less-complex VCE is fairly attractive at small airflows but is of less interest in a high-airflow, low noise setting.

ENGINE COMPARISONS

Experience has taught that the engine and airplane cannot be created in a vacuum, that is, developed separately from each other. The intent of engine and airplane studies has been to cause innovation by identifying problems in missions, installations, engine technical constraints, and finally aircraft performance and range. Figure 13 shows the flow-path of the studies conducted under the SCAR program; ref. 27 elaborates upon the method of analysis and presents some preliminary NASA results. We have demonstrated significant progress by this approach. Subsequent charts will show that both the Pratt & Whitney and General Electric engines have improved significantly as the SCAR studies progressed. In each case, the engine concepts have changed significantly, driven at least in part by the airplane requirements. It will be recalled that at the start of the engine studies, there were many engine concepts; but in all cases the requirements have tended towards variable cycle engine concepts as the best overall solution.

Pratt & Whitney Results

The performance of the Pratt & Whitney engines is illustrated in Fig. 14. Here we have plotted total range as a function of engine corrected airflow. For reference, the lower curve labelled "CTJ" shows the performance obtained by a hypothetical current-technology turbojet engine. The airframe, in this case, is representative of modern NASA and contractor thinking derived from the SCAR program. It is an arrow-wing configuration weighing approximately 700,000 pounds at takeoff and would carry 275 to 300 passengers over ranges up to 4,000 or 4,500 nautical miles. The curve labelled "LBE-430S" is for the modern Pratt & Whitney conventional low bypass mixed-flow engine which embodies SCAR technology advances, but no variable cycle engine features. It represents a major advance over the early engine. In unsuppressed form (the dashed curve) it would appear to be a "winner" at low airflows, but is less attractive at high airflows. Unfortunately, this engine in its present form would require a mechanical sound suppressor; its suppressed performance illustrated by the solid curve, is significantly degraded. Illustrated next is the performance of the variable stream control engine, VSCE-502B. Clearly, it provides excellent performance even at low engine airflows. Its major advantage, however, occurs at higher airflow levels that correspond to lower noise performance. Finally, the rear valve VCE-112C is also fairly competitive at low airflows but less attractive in larger sizes. As previously mentioned, this engine because of its inherent cycle and nozzle geometry characteristics does not receive the full coannular noise benefit. It therefore is less attractive than the curve might suggest for civil uses. For other applications, however, or if a solution to this problem is found, it could well merit further consideration.

The overall results are summarized in bar chart form on the other part of the figure. Here we have shown the range obtainable for several different engines as a function of sideline noise (estimated by the simplified methods of ref. 27) and takeoff field length constraints. The results are shown for a long and short field length and for noise levels of FAR 36 and FAR 36 minus 5. For ease of comparison, both the early turbojet and the LBE-430 have been credited with a mechanical suppressor which confers a 8-dB noise reduction (about the same level as obtained via the coannular benefit). In both cases it is clear that the SCAR conventional engine represents a significant advance over the early turbojet and that the variable stream control engine, the prefered P&W VCE, represents a further advance over the modern conventional engine at airflows corresponding to low takeoff noise.

General Electric Results

Similar results for the General Electric engines are illustrated in Fig. 15. Here are plotted the total range as a function of corrected airflow for the 1970 GE-4 SST engine, for the GE Dual Cycle Engine (which, but for its presumed ability to use a coannular nozzle, is essentially a modernized low bypass mixed flow turbofan engine) and for the Double Bypass Engine. Again for ease of comparison, the GE-4 is credited with an 8 dB high-performance suppressor, while the two VCE's presumably receive about the same benefit from the coannular effect. As was the case with Pratt & Whitney engines it is clear that the modernized turbofan or Dual Cycle engine has achieved a significant improvement over the 1970 SST engine, but the Double Bypass engine in turn represents a major further advance - especially in the high airflow regime which corresponds to low takeoff noise. The bar chart in this figure illustrates exactly the same trends. Range again is shown for long and short takeoff field lengths and for FAR 36 sideline noise and FAR 36 minus 5Db. Noise is again computed by the simplified NASA method of ref. 27, individual contractor's estimates may vary somewhat. It is clearly evident that the Double Bypass variable cycle engine represents the major advance, although the Dual Cycle is fairly competitive at the lower airflows that correspond to greater field lengths and higher noise.

TECHNOLOGY REQUIREMENTS AND PROGRAMS

Mentioned earlier was the fact that one abjective of the SCAR engine studies was to define the technology requirements for making these paper engines real. Figure 16 is a summary of the major technology recommendations presented by Pratt & Whitney and General Electric. Clearly needed are quiet coannular nozzles, underlined on the figure because they are not only critically needed but are unique comments for these engines and not likely to be developed under other programs. In the same category is the low emmissions, efficient duct burner which is characteristic of the Pratt & Whitney engines alone. Also needed are variable geometry fans, flow control valves, advanced low pressure turbines and advanced inlets. There is a major need for low-emmissions primary burners as well as for advancement in hot section technology in general. As previously mentioned, the favored engines obtain improved supersonic performance by increasing the primary burner temperature and speeding up the core as the engine accelerates toward supersonic cruise operation. A consequence of this inverted temperature profile, is an inverted duty cycle in which the engines must spend perhaps 80% of their life times operating at or near the maximum possible turbine inlet temperature. By comparison, a conventional subsonic engine would take off at maximum temperature and then throttle back several hundred degrees when it reaches cruise conditions. Thus, advanced cooling techniques and advanced high temperature materials are of the greatest importance in these engines. Finally, because of the engines' many adjustable features that must be continuously monitored and controlled in flight for safe and efficient operation, there is also a need for advanced digital electronic controls as indicated.

To address some of these needs, NASA has instituted test bed engine programs with both Pratt & Whitney and General Electric. The current program is austere and is relatively slow paced. The basic Pratt & Whitney test item is a rear end assembly comprising a duct burner and a coannular nozzle. In lieu of a large facility air supply, this assembly will be driven by an F100 engine rematched to approach the Variable Stream Control Engine cycle. The duct burner configuration will be selected on the basis of an analytical screening study followed by segment-rig tests of the most promising configurations, before the boiler-plate burner is assembled. Similarly, the quiet coannular nozzle will be evaluated by means of aerodynamic performance and acoustic model tests before the boiler-plate nozzle is constructed.

NASA is also addressing the General Electric technology needs by a test bed engine program. This is being closely coordinated with military programs involving related concepts. Following parallel logic with the Pratt & Whitney work, an existing military engine (J-101 'erivative) will be used as an air supply to test a new aft-end assembly incorporating a quiet coannular nozzle. The military demonstrator includes or can be made to simulate some but not all of the desirable Double Bypass features identified by the SCAR studies. It can be rematched to provide an excellent simulation of the selected cycle at takeoff conditions, and a more limited simulation at other conditions. The design of the quiet nozzle will be established by further analysis and aeroacoustic model tests before the full-sized assembly is constructed. In addition, a new variable geometry front fan will be rig tested separately from the engine/nozzle test. The fan rig test assembly will be sized to be compatible with a future, more advanced testbed engine embodying all significant features of the Double Bypass Engine concept.

In summary, the presently planned testbed programs will accomplish several objectives; namely, to test for each company - General Electric and Pratt & Whitney - the two most critical, most unique technology requirements identified by their SCAR engine studies. At Pratt & Whitney this comprises a clean, efficient duct burner and a quiet coannular nozzle. For General Electric it includes a variable-flow front fan block and a quiet annular nozzle. It is emphasized that these are critical items, unique to the favored engines, and not likely to be developed elsewhere. Hopefully, additional needs appearing in Fig. 16 will be at least partially addressed by other NASA or military programs. If not, a sizeable augmentation of the testbed and related SCAR programs may be necessary in the future.

CONCLUDING REMARKS

At this point, we have reviewed the evolution of two groups of VCE concepts and shown how they have been favorably impacted by design simplification and by technology advancements in many areas - particularly in the area of acoustics. Parallel advancements have been achieved in the airframe area by other parts of the SCAR program.

What is the overall payoff from these developments? In Fig. 17 is shown a plot of subsonic mission leg length versus the airplane's total range capability. Several city-pair combinations of economic interest are spotted on the figure. The line at the left indicates the estimated performance of the 1970 United States SST at one point near the close of that program. The nearly vertical band at the right indicates the performance now predicted for an advanced supersonic transport using variable cycle engine concepts and taking advantage of the SCAR technology advancements that have been discussed. As indicated by the arrows between the lines, these advancements are due to improved engine technology, aerodynamic and structural technology advances and the variable cycle concepts. Clearly, a major improvement in the airplane's ability to serve potentially attractive markets has been identified on paper.

What can be done to make these paper engines real? By the SCAR studies we believe that we are identifying what needs to be done to develop a viable option for some future date. By the testbed programs we are addressing the unique and most critical components for each of the favored VCEs. Admittedly, there are other needs which are not now being addressed. But we believe that if the testbed programs are steadfastly pursued to their successful conclusions, the logical next steps will be forthcoming.

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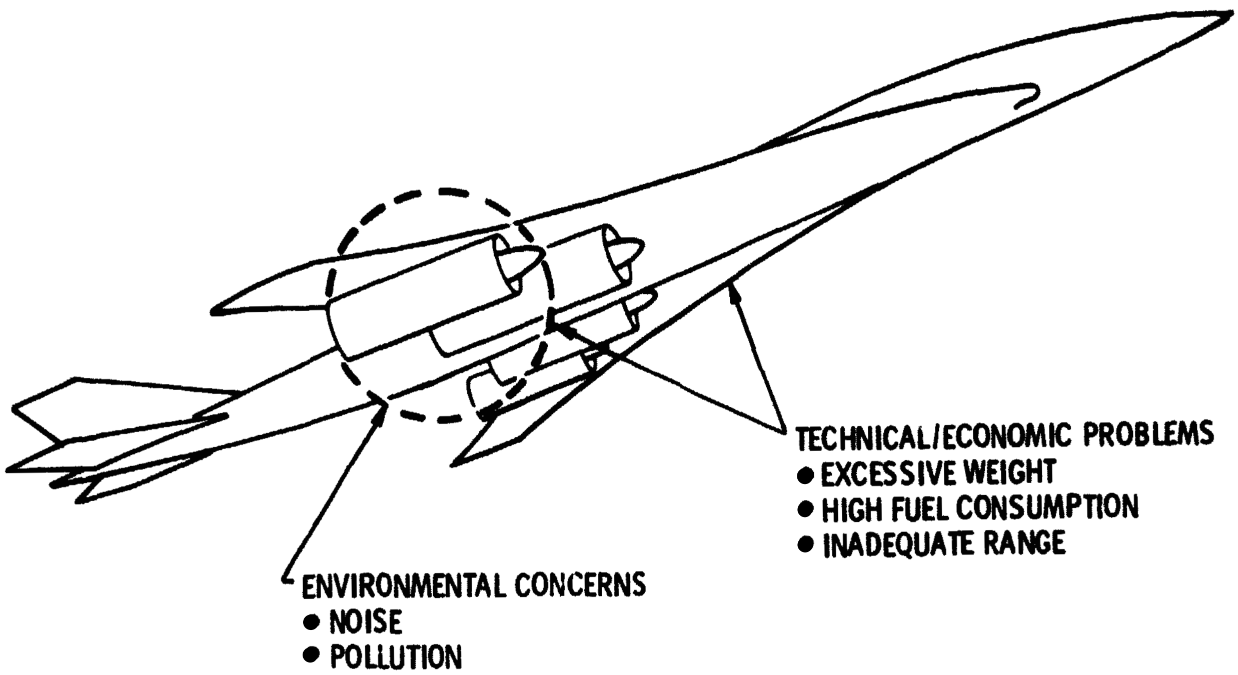

Figure 1. - The 1970 U.S. SST program.

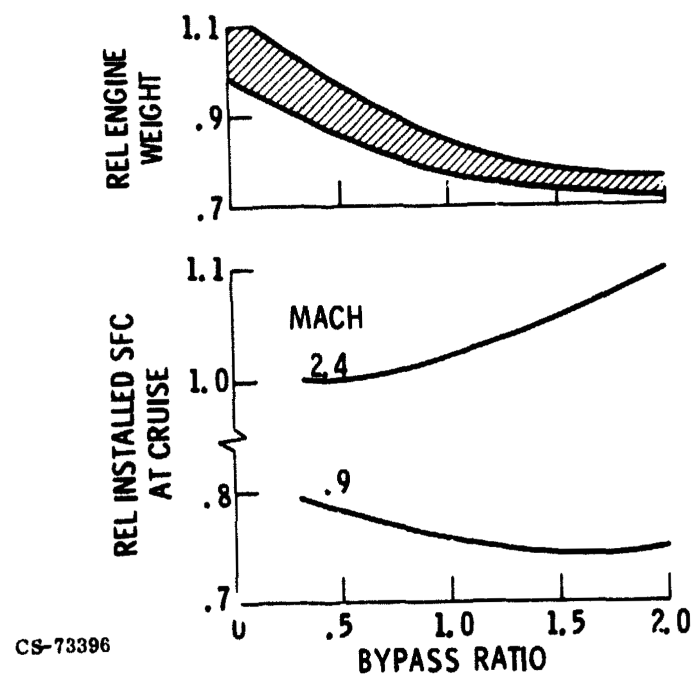

Figure 2. - Factors to consider in cycle selection.

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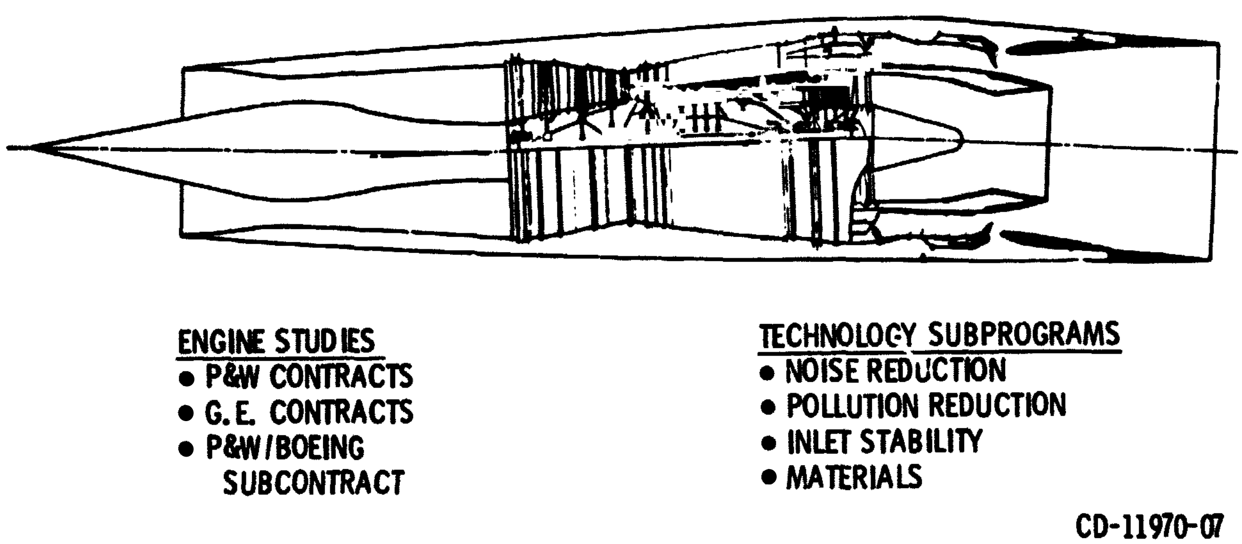


Figure 3. - The SCAR propulsion program.

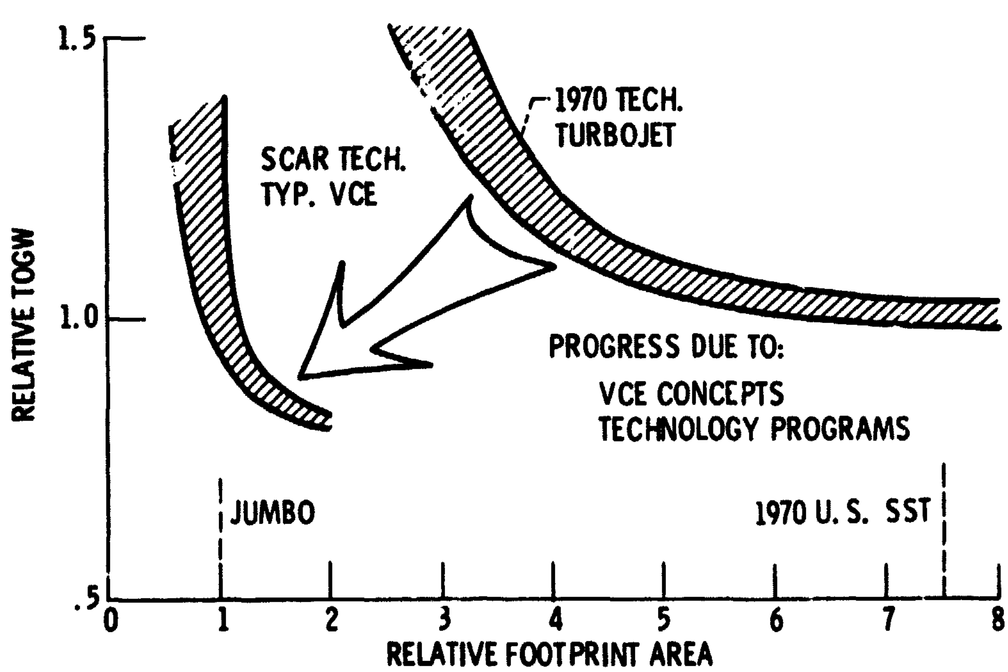


Figure 4. - SST progress since 1970.

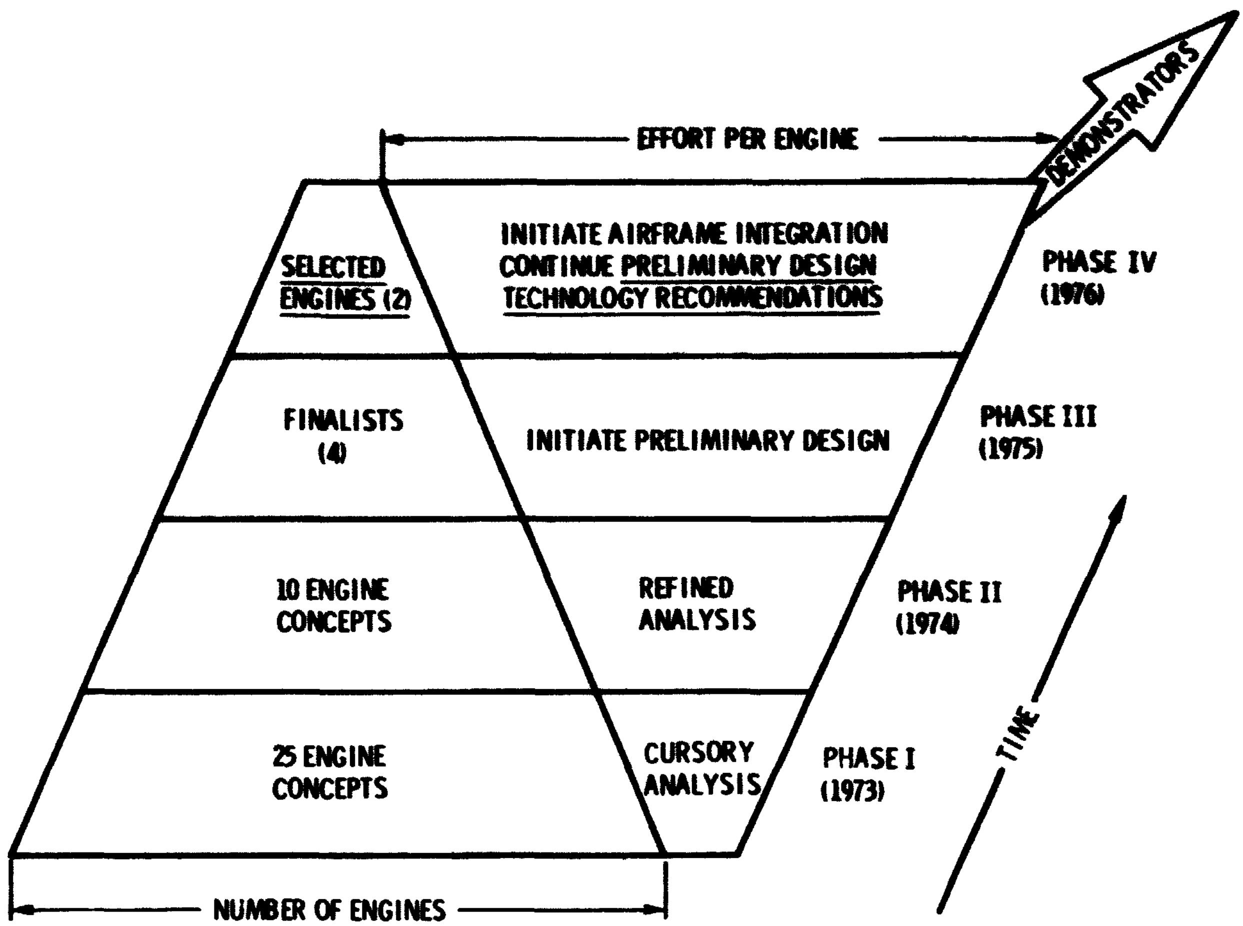


Figure 5. - Evolution of SCAR engine studies.

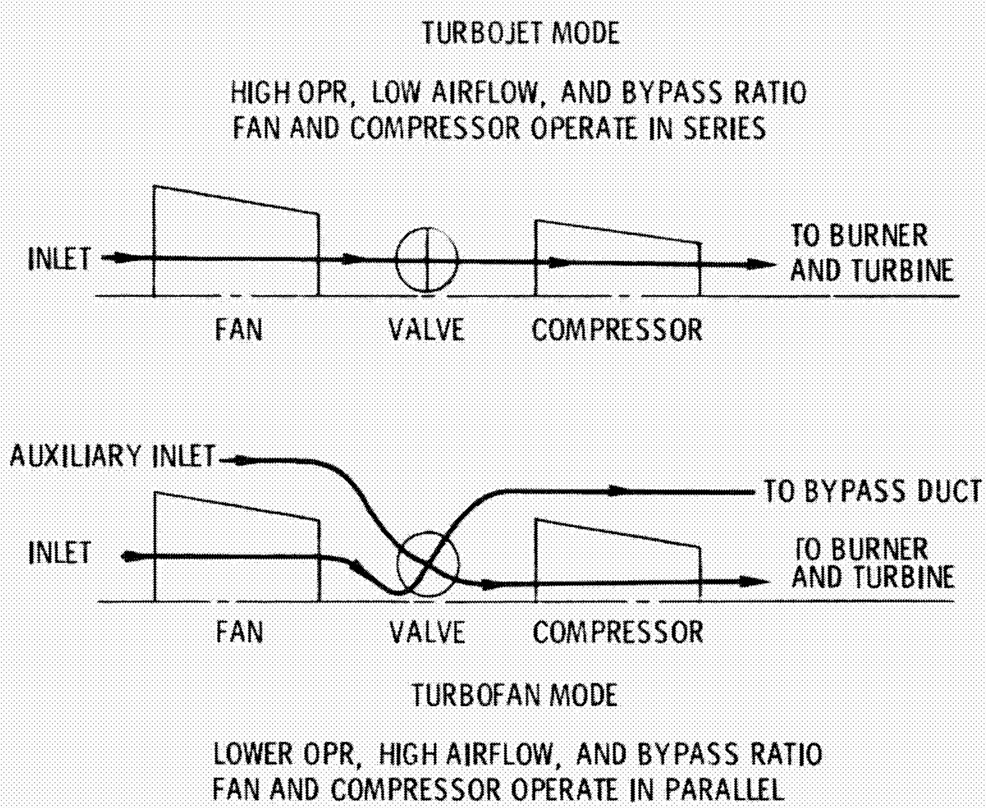


Figure 6. - Series-parallel valved VCE concept.

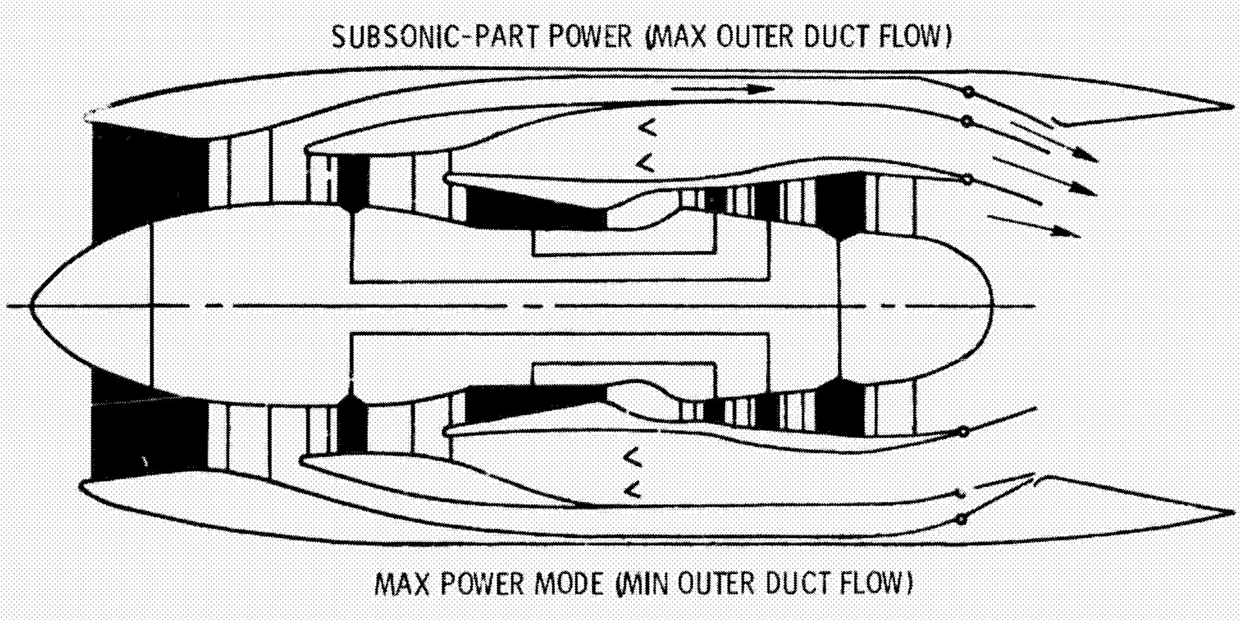


Figure 7. - 3-Rotor double bypass or modulating airflow engine concept.

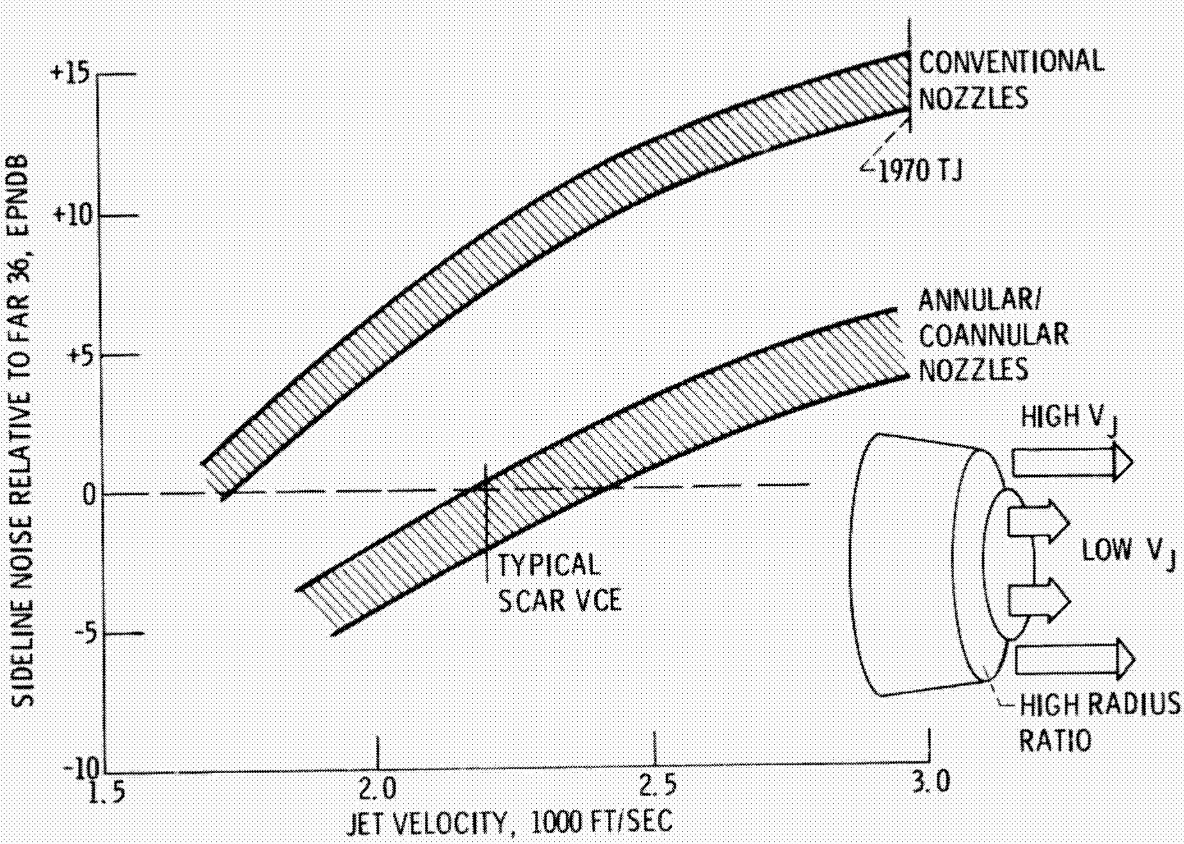


Figure 8. - Coannular noise benefit.

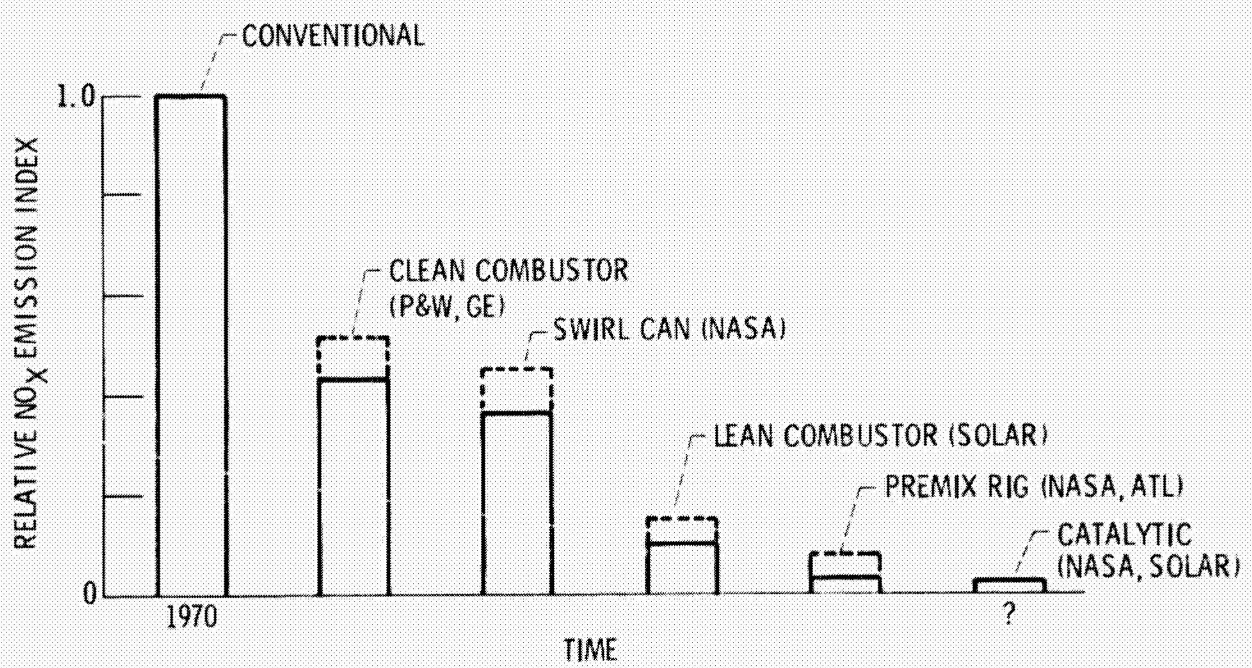
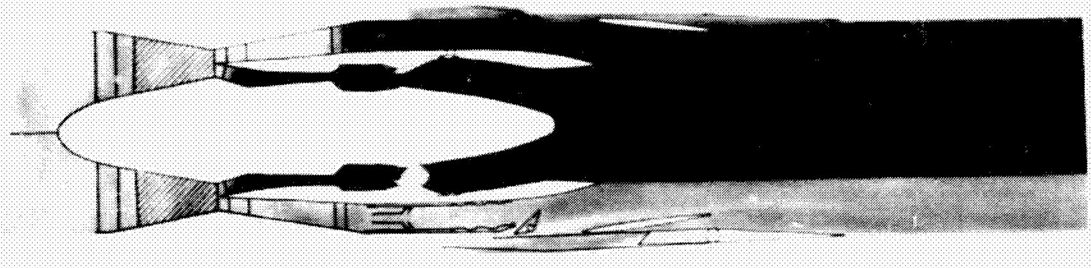


Figure 9. - Status of cruise NO_X emission experiments.

P&W VSCE-502B
TAKEOFF AND SUBSONIC OPERATION

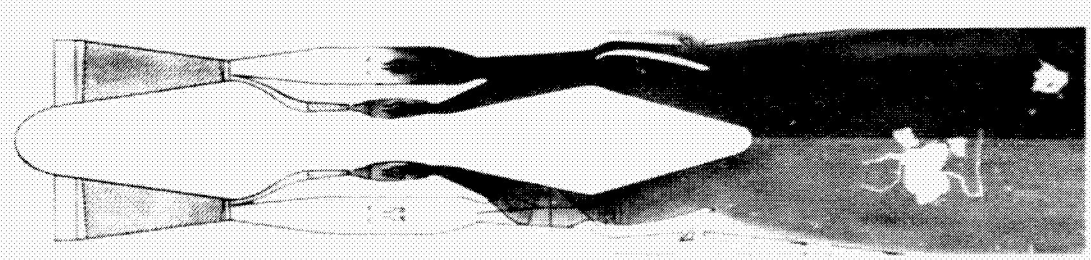


SUBSONIC CRUISE OPERATION

CD-11970-07
C-76-720

Figure 10. - Variable stream control engine.

P&W VCE-112B
SUPERSONIC OPERATION



SUBSONIC CRUISE OPERATION

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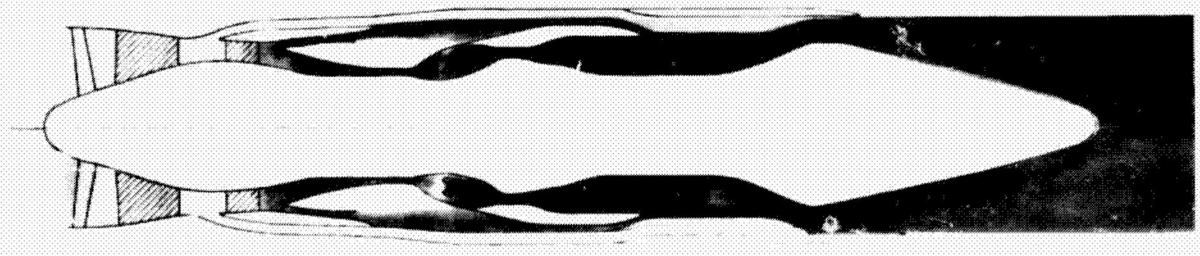
Figure 11. - Rear valve variable cycle engine

TAKEOFF AND SUPERSONIC OPERATION



CLIMB AND SUPERSONIC CRUISE

CD-11971-07
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Figure 12. - Double bypass engine GE VCE concept.

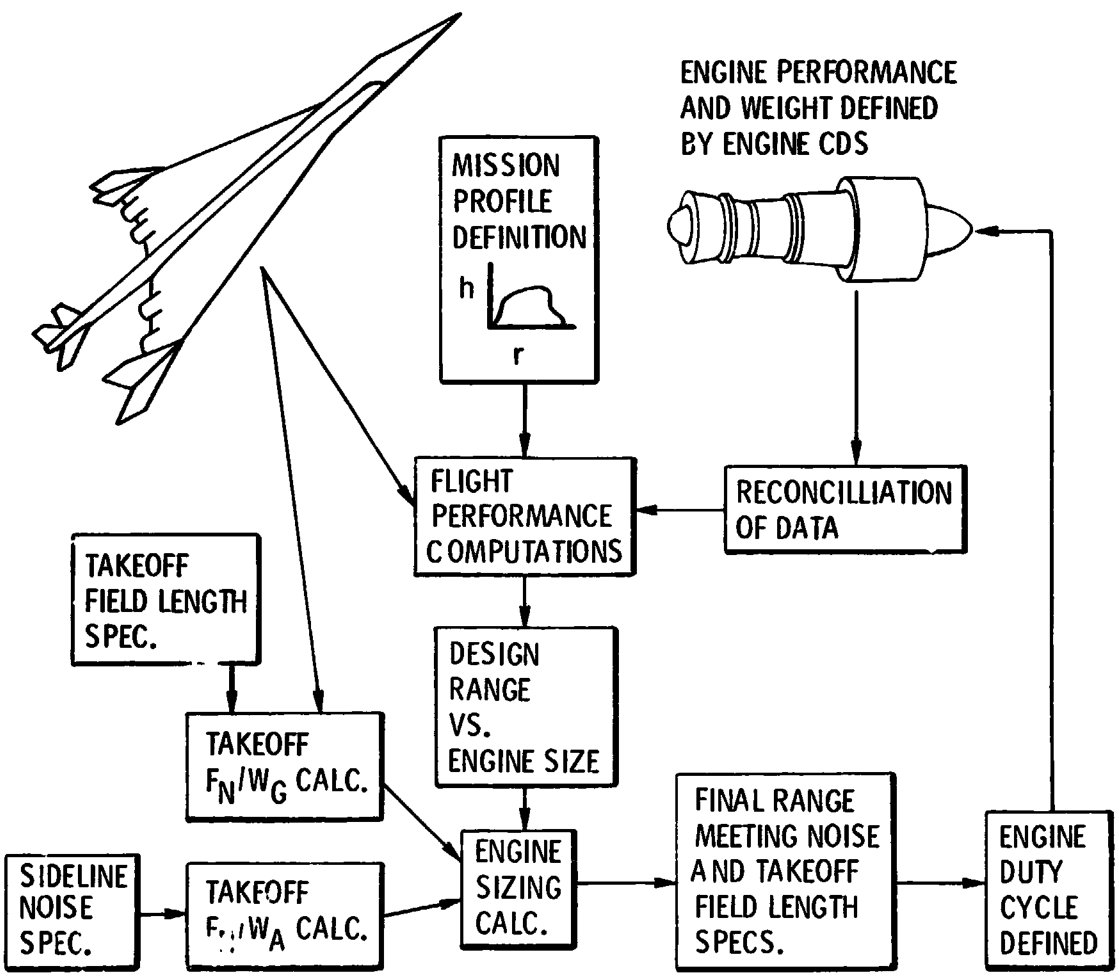

Figure 13. - Engine evaluation scheme.

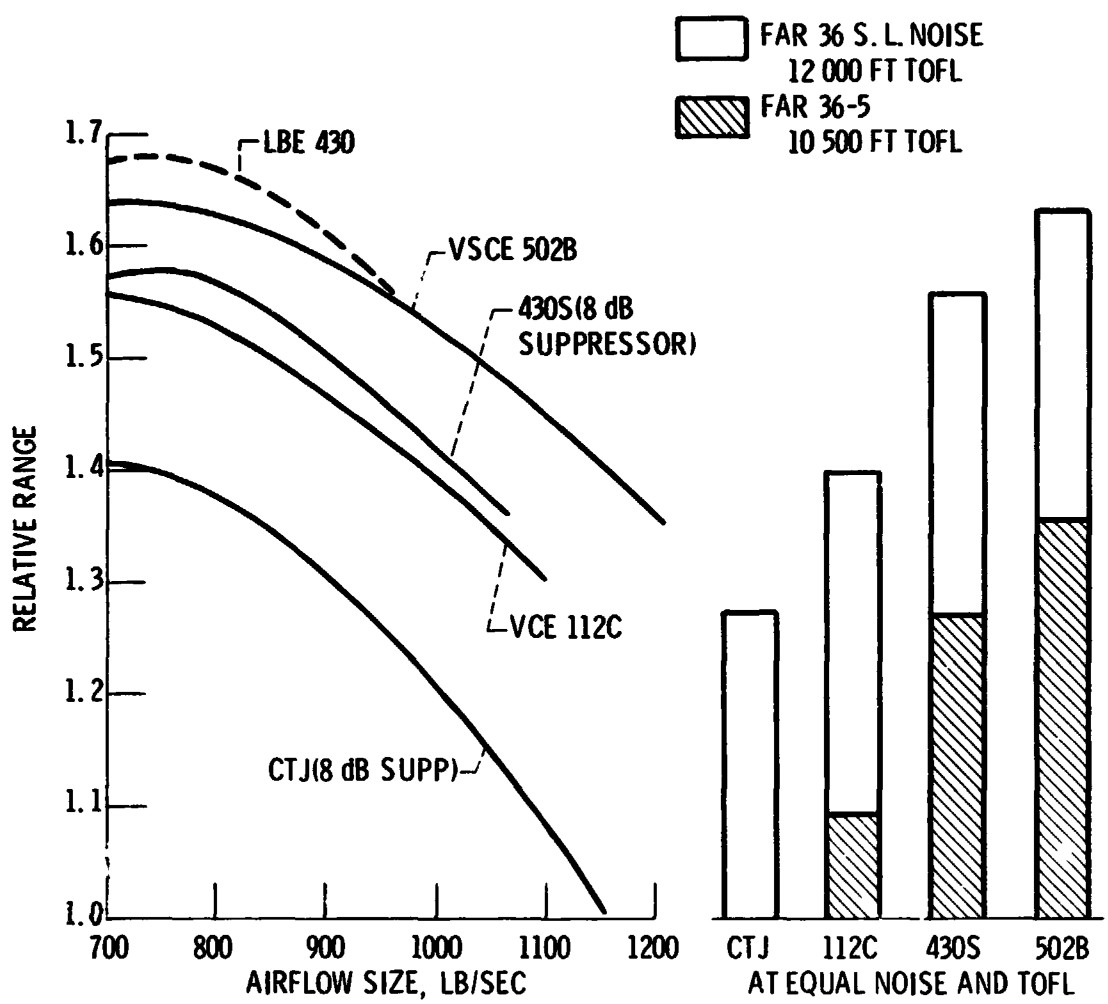

Figure 14. - Pratt & Whitney engine comparison.

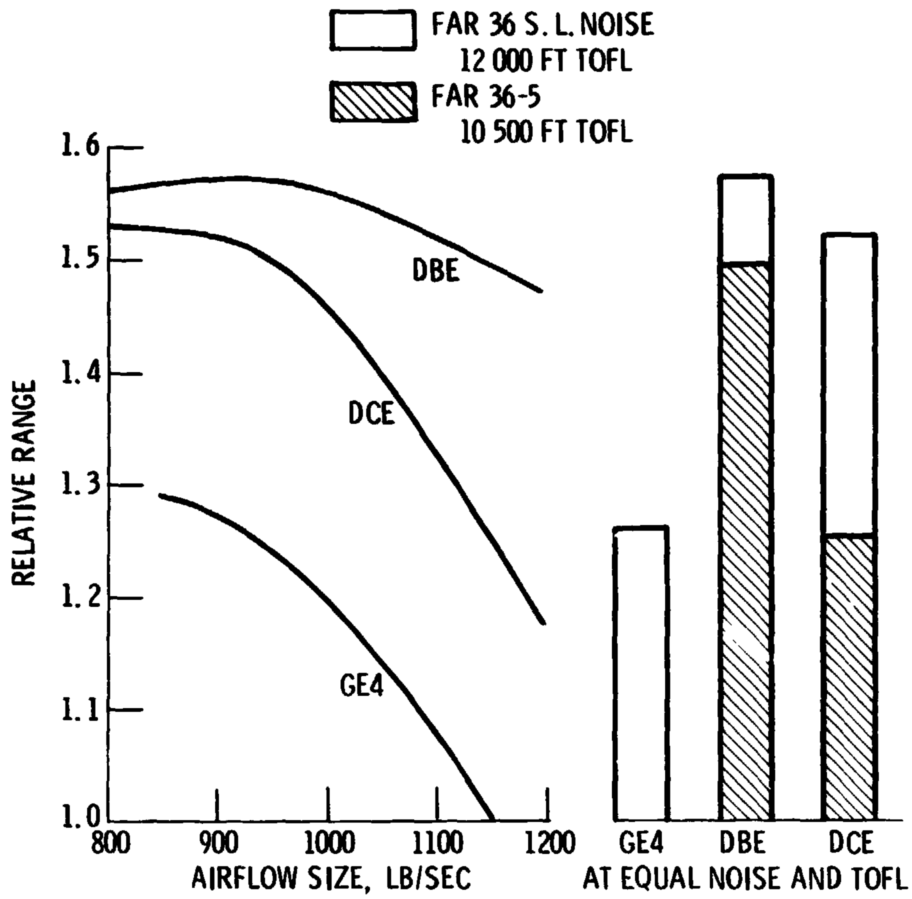

Figure 15. - General Electric engine comparison.

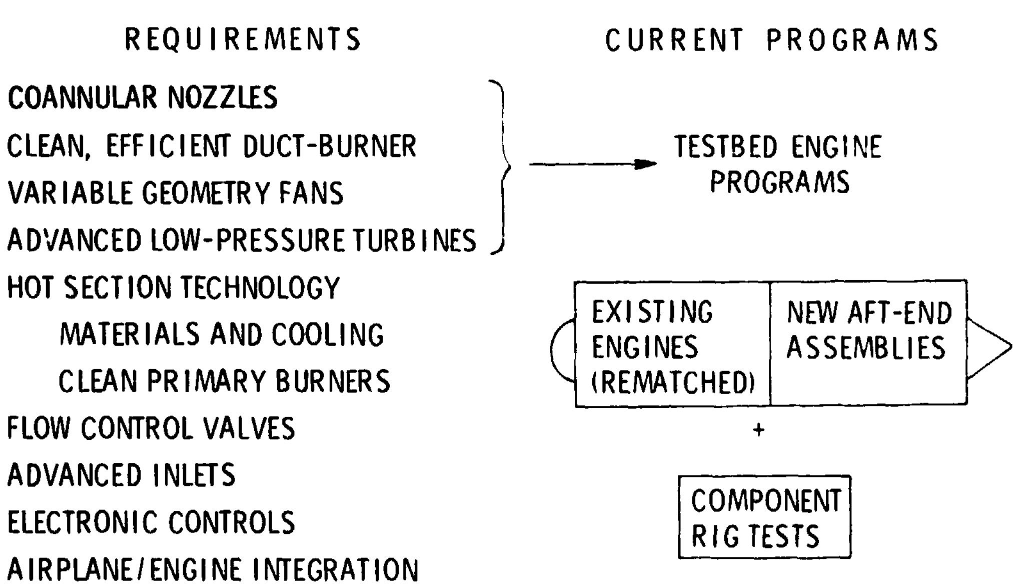

Figure 16. - Summary of VCE technology requirements and current programs.

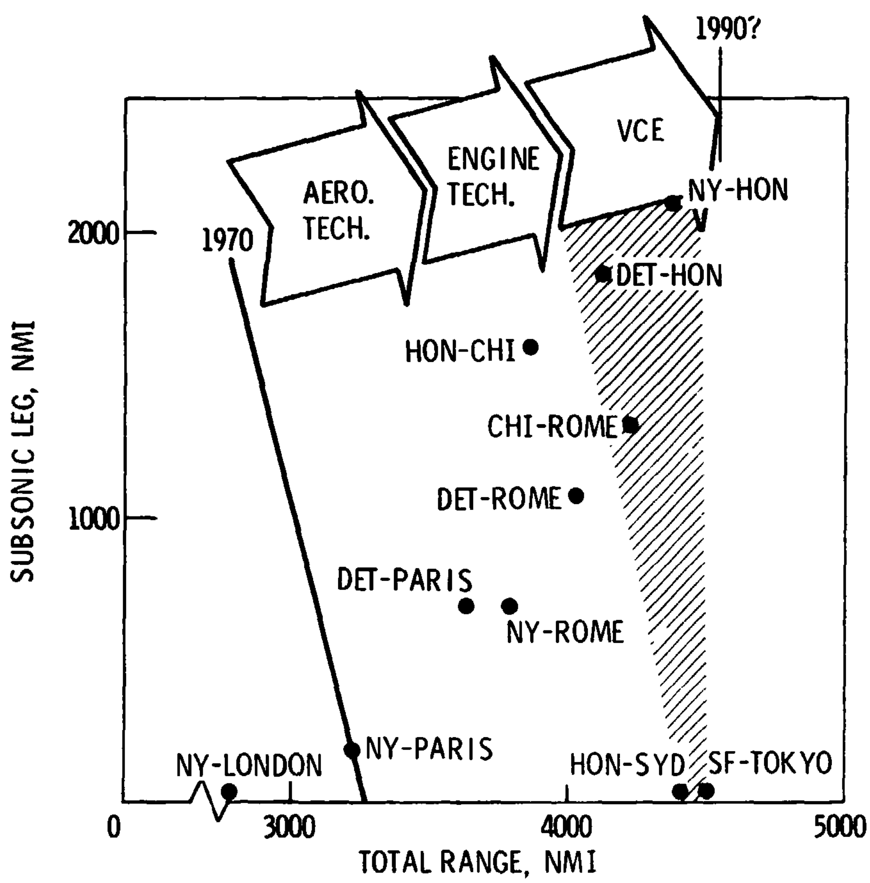

Figure 17. - SCAR technology payoffs.